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International Year of Astronomy Invited Review on Exoplanets

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ABSTRACT. Just 14 years ago the Solar System represented the only known planetary system in the Galaxy, and conceptions of planet formation were shaped by this sample of one. Since then, 320 planets have been discovered orbiting 276 individual stars. This large and growing ensemble of exoplanets has informed theories of planet formation, placed the Solar System in a broader context, and revealed many surprises along the way. In this review I provide an overview of what has been learned from studies of the occurrence, orbits, and physical structures of exoplanets. After taking a look back at how far the field has advanced, I will discuss some of the future directions of exoplanetary science, with an eye toward the detection and charactarization of Earth-like planets around other stars.

Online material: color figures

1. INTRODUCTION

The state of knowledge on planetary systems has undergone a major revolution over the past 14 years. Starting with the discovery of the first exoplanet orbiting a normal, hydrogen-burning star in 1995 (Mayor & Queloz 1995), the sample of known exoplanets has rapidly expanded from a sample of one to 320 individual planets residing in 276 planetary systems.[2] The majority of these planets were detected by either Doppler techniques or by photometric transit surveys, and therefore have well-characterized orbits with system parameters amenable to uniform statistical analyses (Butler et al. 2006; Torres et al. 2008). Additional planets have been discovered using gravitational microlensing and a handful of planets have even been directly imaged (Beaulieu et al. 2006; Gaudi et al. 2008; Kalas et al. 2008; Marois et al. 2008). The occurrence rates, orbital properties, and physical characteristics of these worlds inform our understanding of the formation and orbital evolution of planets in general, and the origin of our solar system in particular.

2. PLANET OCCURRENCE

The search for exoplanets began with a humble and ancient question: do planets exist around other stars? Hints initially emerged with the detection of Kuiper Belt-like dust disks around young stars such as Vega and β Pic (Aumann et al. 1984; Smith & Terrile 1984), the radial velocity (RV) detection of progressively smaller substellar companions (Latham et al. 1989), and the discovery of "pulsar planets" (Wolszczan & Frail 1992). Since then, the study of planet occurrence has evolved from a question of existence to a full-fledged statistical study of hundreds of systems. Knowledge of where planets are found and their relative frequencies around stars of various types provides valuable insights into the planet formation process and guides future planet search efforts.

Doppler surveys of thousands of stars have shown that among the Sun-like, FGK stars in the solar neighborhood, roughly one in 10 harbors a giant planet with a period $P <$ 2000 days and a minimum mass greater than half the mass of Jupiter ($M_P \sin i > 0.5\ M_{\rm Jup}$; Cumming et al. 2008). The distribution of detectable planets as a function of semimajor axis, $dN/d\log a$ is roughly flat out to 1 AU, and then rises toward ~4.5 AU, a cutoff corresponding to the decade-long time baselines of the Doppler-based planet searches (Fig. 1). Careful extrapolation to larger semimajor axes indicates that 17–19% of stars harbor a giant planet within 20 AU (Cumming et al. 2008), and the planets discovered by direct imaging suggest that planets exist out to semimajor axes of hundreds of AU (Kalas et al. 2008; Chiang et al. 2008; Veras et al. 2009).

Additional insight has been gained by studying planet occurrence as a function of stellar properties. The properties of stars are closely related to the properties of the circumstellar environment during the early epoch of planet formation. Planet-host stars therefore represent an important link between the systems detected today and the processes of planet formation that took place in the past.

For example, studies of the chemical compositions of planet-host stars reveal a strong correlation between stellar metallicity and planet occurrence (Gonzalez 1997; Santos et al. 2004; Fischer & Valenti 2005). The probability of a star having a detectable planet rises from roughly 3% around stars with solar iron abundance ($[\mathrm{Fe/H}] = 0$), to $>15\%$ for stars with

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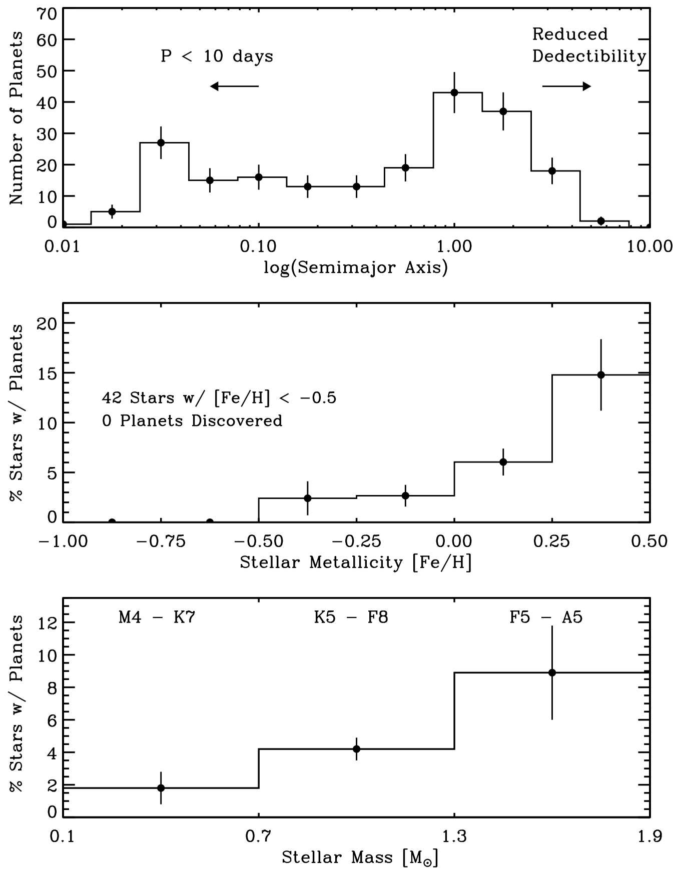

FIG. 1.—*Top:* Distribution of Doppler-detected exoplanets as a function of semimajor axis. 10% of stars have planets within 5 AU (Cumming et al. 2008). *Middle and bottom*: The occurrence rate of planets rises as a function of metallicity (Fischer & Valenti 2005) and stellar mass (Johnson et al. 2007a).

$[\mathrm{Fe/H}] > +0.25$ (Fig. 1; Fischer & Valenti 2005). The planet-metallicity correlation is currently best understood in the context of the core accretion theory of planet formation, in which planets are formed through the collisional buildup of refractory material in the protoplanetary disk (Pollack et al. 1996; Ida & Lin 2004). A higher stellar metallicity observed today is a reflection of the higher dust content of the disk while planets were forming.

Mass is another stellar property closely related to the surface density of solids in the disk midplane, and the core accretion model predicts that planet frequency should correlate with stellar mass (Laughlin et al. 2004; Ida & Lin 2005; Kennedy & Kenyon 2007). This prediction has been confirmed by Doppler surveys of stars at either end of the mass scale (Fig. 1). At the low-mass end, only four out of $\approx$300 M dwarfs in various Doppler surveys have been found to host a Jupiter-mass planet (Marcy et al. 1998; Butler et al. 2006; Johnson et al. 2007a; Bailey et al. 2008). At the other end of the scale, studies of evolved F and A stars on the subgiant and giant branches (Reffert et al. 2006; Sato et al. 2007; Niedzielski et al. 2007) have revealed an enhanced planet occurrence rate around high-mass stars, rising from $<2\%$ around M dwarfs, to approximately 9% around F and A stars (Lovis & Mayor 2007; Johnson et al. 2007a).

The correlation between planet occurrence and stellar properties not only informs theories of planet formation, but also guides the target selection of future planet searches. The increased "planeticity" of metal-rich stars has been harnessed by several metallicity-biased planet searches to find large numbers of short-period planets around nearby ($d \lesssim 200$ pc) stars (Fischer et al. 2005; da Silva et al. 2006). The correlation between stellar mass and planet occurrence will be an important consideration for the target selection of current and future direct-imaging planet search missions. Indeed, the first imaged planet candidates were discovered around the $\sim 2\ M_\odot$ A-type stars Fomalhaut, HR 8799, and β Pic (Kalas et al. 2008; Marois et al. 2008; Lagrange et al. 2009).

3. THE OBSERVED PHYSICAL AND ORBITAL PROPERTIES OF EXOPLANETS

Doppler surveys have uncovered a wealth of information about the orbital characteristics of exoplanets. Giant planets around other stars have a wide range of semimajor axes and orbital eccentricities (Udry et al. 2003; Butler et al. 2006). In contrast to the nearly circular orbits of the Solar System gas giants, the orbits of exoplanets range from circular to cometlike, spanning the range $0 \le e \le 0.93$, with a median eccentricity of 0.24 for $a > 0.1$ AU (Fig. 2).

The distribution of exoplanet minimum masses, $M_P \sin i$, is well fit by the power-law relationship $dM_P/dN \propto M_P^{-1.4}$ (Fig. 2), indicating that smaller Jovian planets form more readily than massive "super-Jupiters" and brown dwarfs. The paucity of planets with $M_P \sin i > 10\ M_{\mathrm{Jup}}$ is known as the "brown dwarf desert," and high-contrast imaging surveys show that companions in this mass range are rare even out to large semimajor axes (McCarthy & Zuckerman 2004; Grether & Lineweaver 2006). However, there are indications that the most massive Jovian planets with $M_P \sin i \gtrsim 2\ M_{\mathrm{Jup}}$ and wide orbits are more prevalent around massive stars (Lovis & Mayor 2007; Johnson et al. 2007b; Sato et al. 2008). The observed eccentricity distribution is currently best reproduced by simulations of dynamical interactions among multiple planets immediately following the dissipation of the protoplanetary gas disk (Chatterjee et al. 2008; Juríc & Tremaine 2008; Ford & Rasio 2008; however, see references therein for alternative models).

Doppler surveys have shown that 1.2% of stars have planets with orbital periods $P < 10$ days, corresponding to $a \lesssim 0.1$ AU (Marcy et al. 2005). These short-period planets are commonly referred to as "hot Jupiters," and they likely did not form in situ due to the high temperatures and low surface densities of the inner regions of protoplanetary disks. Instead, hot Jupiters and other close-in planets most likely formed beyond the "ice line" at a few AU, and then migrated inward to their present

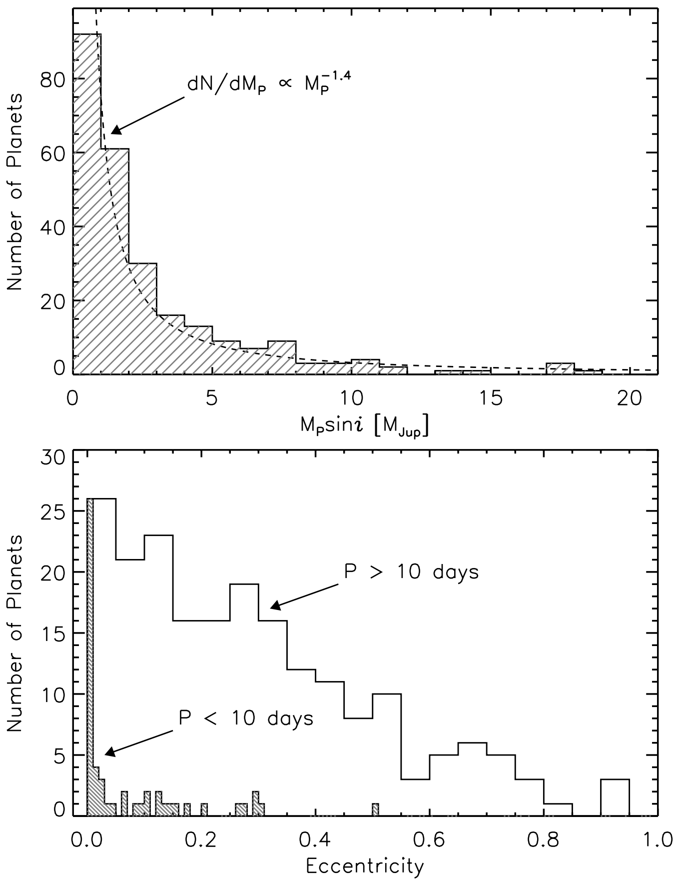

FIG. 2.—*Upper:* Distribution of minimum masses ($M_P \sin i$) for all Doppler-detected planets. The dashed line shows the best-fitting power law. *Lower:* Eccentricity distribution of Doppler-detected planets for $P < 10$ days (*shaded*) and $P > 10$ days (*unshaded*).

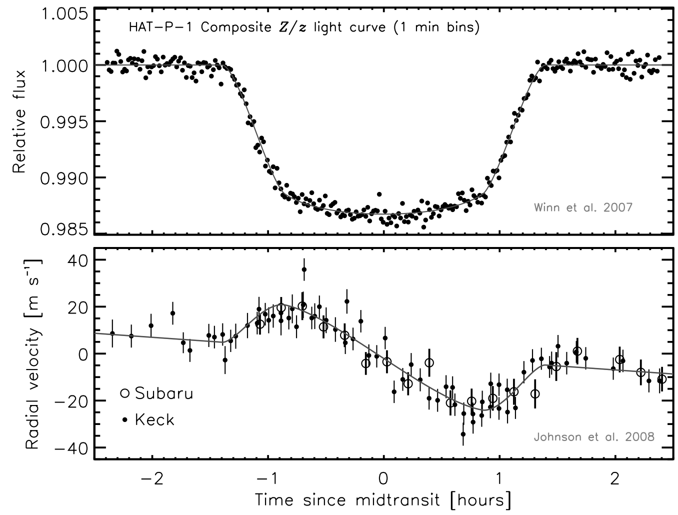

FIG. 3.—Transit observations of the exoplanet HAT-P-1b, which was discovered by the HAT-Net wide-field transit survey (Bakos et al. 2007). The planet has a mass $M_P = 0.53\ M_{\rm Jup}$, and an orbital period $P = 4.465$ days. *Upper:* A composite transit light curve constructed from 7 individual photometric data sets (Winn et al. 2007). The photometry was phased by subtracting the midtransit time from each light curve. The best-fitting model gives a planet radius $R_P = 1.225 \pm 0.056\ R_{\rm Jup}$ *Lower:* Phased radial velocity measurements made during three transits, illustrating the Rossiter-McLaughlin (RM) effect. The shape of the RM waveform yields the projected spin-obit angle. The HAT-P-1 planetary system is well aligned with a spin-orbit angle of 3.7 ± 2.1 degrees (Johnson et al. 2008). See the electronic edition of the PASP for a color version of this figure.

locations (Lin et al. 1996; Trilling et al. 1998). The process of inward migration is now thought to be a ubiquitous and integral feature of how planets form (Alibert et al. 2005).

Planets with orbits that are serendipitously viewed edge-on transit their host stars and provide valuable additional information about the physical and orbital characteristics that cannot be studied by Doppler techniques alone (Charbonneau et al. 2005; Winn 2008). The sample of known exoplanets includes 52 examples of well-characterized transiting systems. While the brightest examples ($V < 8$) come from photometric follow-up of Doppler-detected planets, the majority of transiting planets were detected by wide-field photometric surveys (Konacki et al. 2003; Alonso et al. 2004; Bakos et al. 2007; Cameron et al. 2007; McCullough et al. 2006). By monitoring hundreds of thousands of stars per night using networks of small-aperture, wide-field cameras, these surveys have uncovered a diverse collection of short-period planets with a wide range of masses, radii, and orbital configurations (Southworth 2008; Torres et al. 2008).

The orbit solution of Doppler-detected planets yields the minimum mass of the planet, $M_P \sin i$, but the light curve of a transiting planet yields a direct measure of the planet's inclination, providing an absolute measure of the planet's mass (assuming the stellar mass is known; Henry et al. 2000; Charbonneau et al. 2000). The depth of the photometric dip is related to the planet's radius (upper panel of Fig. 3). The mass and radius together give the mean density, which can be compared to theoretical models of planetary interiors to provide a glimpse of their interior structures (Sato et al. 2005; Laughlin et al. 2005). Modeling efforts of this type have revealed that enhanced heavy-element abundance, ostensibly in the form of a large solid core, is a common feature of hot Jupiters (Gillon et al. 2007; Burrows et al. 2007a; Fortney et al. 2007). The growing sample of transiting planets exhibits heavy-element masses ranging from tens of earth masses up to ~100 $M_\oplus$. For comparison, Jupiter is composed of 1–39 $M_\oplus$ of heavy elements, and has a core mass ranging from 0–11 $M_\oplus$ (Saumon & Guillot 2004). Notably, the core masses of transiting planets correlate with the metal abundances of the host stars, a finding that lends additional support for the core accretion model of planet formation (Guillot et al. 2006; Burrows et al. 2007a; Torres et al. 2008).

While many transiting exoplanets have large cores, others have radii that far exceed the predictions of the current suite of planetary interior models, even if a heavy-element core is omitted. These bloated planets pose serious challenges to theoretical models of planetary interiors (Brown et al. 2001; Mandushev et al. 2007; Baraffe et al. 2003). The solution may lie in improved stellar age estimates, revised atmospheric opacities or a better understanding of chemistry and dynamics in planetary atmospheres (Chabrier et al. 2004; Burrows et al. 2007b).

Planet transits also yield a measure of an additional fundamental orbital characteristic of planetary systems: the spin-orbit alignment (Queloz et al. 2000). Measurements of a host star's radial velocity during the transit of its planet can reveal anomalous Doppler-shift variations known as the Rossiter-McLaughlin effect (Winn et al. 2005; Gaudi & Winn 2007), and the time-dependent variation of this effect is related to the projected angle between the star's spin axis and the planet's orbit normal, λ (lower panel of Fig. 3). The spin-orbit angle is a fundamental property of planetary systems, analogous to the eccentricity and semimajor axis. The majority of measured exoplanet spin-orbit angles are consistent with $\lambda = 0$, and an isotropic distribution for λ can be ruled out with high confidence, even after accounting for projection effects (Winn et al. 2005; Fabrycky & Winn 2009). This result suggests that the dominant mechanism responsible for the inward migration of planets preserves spin-orbit alignment (although Hébrard et al. [2008] and Winn et al. [2009] present a notable exception with the misaligned XO-3 system).

Half an orbital period after a planet transit, another observational opportunity arises when the planet passes behind the parent star. Observations made during these occultation events provide a means of detecting light from the planet itself, as revealed by the flux decrement caused by the star blocking the light from the planet (Deming et al. 2005; Charbonneau et al. 2005). The variation in the depth of the occultation light curve measured in different bandpasses provides a measure of the planet's emission spectrum, which can then be compared to theoretical models to gain insights into the characteristics of planetary atmospheres. Observations of this type made with space-based facilities such as the *Spitzer Space Telescope,* the *Hubble Space Telescope,* and MOST, have revealed evidence of temperature inversions in the atmospheres of some planets (Knutson et al. 2009); detected molecules such as H_2O and CO_2 in their atmospheres (Grillmair et al. 2008); placed limits on their wavelength-dependent bond albedos (Rowe et al. 2008); and have been used to measure their eccentricities based on the time interval between primary and secondary eclipse (Demory et al. 2007).

4. MULTIPLICITY

There are 32 known multiplanet systems orbiting nearby stars with well-characterized orbits (Fig. 4; Wright et al. 2008; Udry et al. 2007). These systems, together with single-planet systems with additional radial velocity trends, comprise 30% of all known planetary systems within 200 pc. Five of the

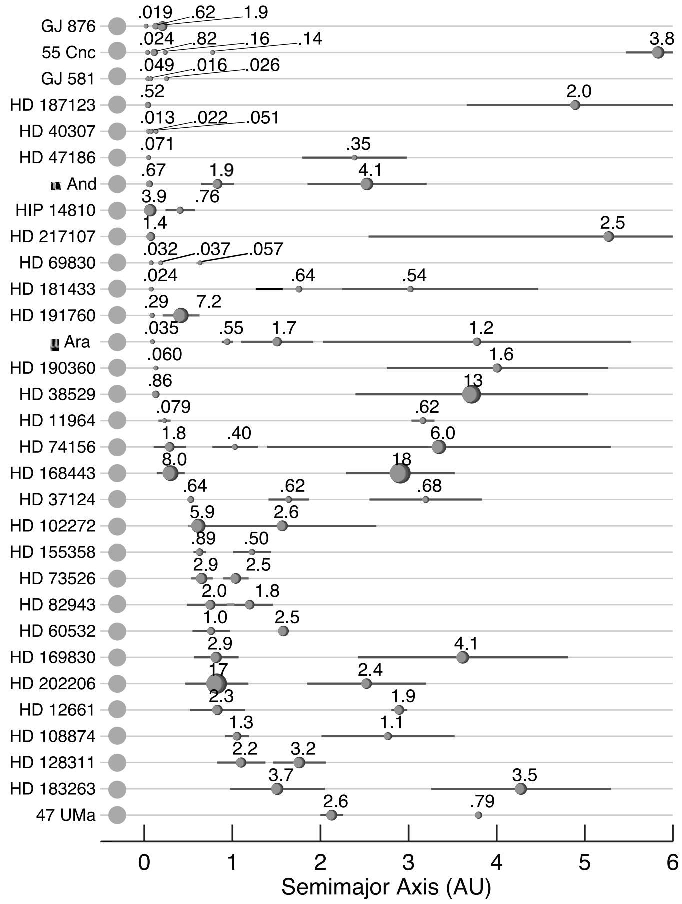

FIG. 4.—Chart showing the semimajor axes and minimum masses for the 31 known planetary systems containing more than one planet (data from Wright et al. [2008], as updated by Correia et al. [2009], Mayor et al. [2009], and Niedzielski et al. [2009]). The horizontal lines under each planet indicate the distance between periapse and apoapse for eccentric orbits. The sizes of the planet symbols scale as $(M_P \sin i)^{1/3}$, and the labels denote the planet mass in units of M_J. See the electronic edition of the PASP for a color version of this figure.

known multiplanet systems are in mean-motion resonances, and two are known to contain four or more planets: the system of five planets around 55 Cnc and the four-planet system around μ Ara (Fischer et al. 2008; Pepe et al. 2007). The characterization of multiplanet systems requires intensive follow-up observations, and the additional scrutiny has resulted in the detection of some of the least massive planets currently known. The Gl 876, 55 Cnc, and μ Ara systems all contain low-mass planets that were discovered by intensive Doppler follow-up, with $M_P \sin i = 5.89$, 10.8 and 15 $M_\oplus$, respectively (Rivera et al. 2005; McArthur et al. 2004; Fischer et al. 2008; Pepe et al. 2007). The discovery of multiplanet systems has been aided by improvements to the attainable Doppler precision, resulting in planetary systems containing multiple Neptune- and sub–Neptune-mass planets (Vogt et al. 2005; Lovis et al. 2006; Mayor et al. 2009). The increasing time baselines of Doppler surveys, together with the sensitivity of microlensing surveys, are bringing solar system analogs within reach (Wright et al. 2007; Gaudi et al. 2008).

Multiplanet systems are valuable testing grounds for theories of planet formation and migration (Ford 2006; Terquem & Papaloizou 2007). For example, planets should form at arbitrary locations within the protoplanetary disk, and yet several multiplanet systems have been detected in mean-motion resonances. These systems indicate that systems of planets migrate inward and are subsequently captured into resonant configurations (Marcy et al. 2001; Correia et al. 2009; Raymond et al. 2008). Comparisons between the properties of multiplanet systems and those of systems containing only a single detectable planet provide important observational constraints for theories of planet-planet and disk-planet interactions (Alibert et al. 2005; Ford et al. 2005).

5. FUTURE DIRECTIONS

The low-mass planets in short-period orbits detected by Doppler-based planet searches (Mayor et al. 2009) and those at wider separations detected via gravitational microlensing (Bennett et al. 2008) point the way toward the future of exoplanet science: the detection and characterization of Earth-like planets. One of the primary goals of the study of exoplanets is to determine whether solar systems like our own exist elsewhere in the Galaxy (Lunine et al. 2008). However, the detection of an Earth-mass planet in the habitable zone of a Sun-like star (late F-type to early K) poses a considerable technical challenge. These small planets induce radial velocity variations of $\sim$10 cm s^{-1}, astrometric variations of a few microacrseconds, transit depths of $\sim 10^{-4}$, and have planet-star contrast ratios of 10^{-10} to 10^{-7}, for reflected light and thermal emission, respectively (e.g., Schneider 2002).

One immediate method of circumventing these technical hurdles is to first search for habitable worlds around M dwarfs. The amplitude of the Doppler variations induced by a planet of a given mass in the habitable zone of a star scale as $K \propto M_*^{-3/2}$, and the transit depth scales as M_*^{-2} (assuming $R_* \propto M_*$ for the lower main sequence). The detection sensitivities are therefore an order of magnitude higher around a $0.25\ M_\odot$ M dwarf compared to a solar-type star. Targeted photometric and Doppler searches for transiting terrestrial planets in the habitable zone of M dwarfs are currently underway (Butler et al. 2004; Bonfils et al. 2005; Irwin et al. 2008). The low-mass planetary system tantalizingly close to the habitable zone of the $0.4\ M_\odot$ M Dwarf Gl 581 demonstrates the promise of searching for planets around low-mass stars (Udry et al. 2007).

The occurrence rate of terrestrial planets around Sun-like stars can be estimated from the frequency of exoplanets with masses intermediate to Earth and Neptune, commonly known as "super-Earths." Planets with masses $\sim 10\ M_\oplus$ in short-period orbits are readily detectible by Doppler surveys capable of $\sim$1 m s^{-1} precision, and several dedicated searches are currently underway using HARPS and Keck/HIRES (Mayor et al. 2009; Howard et al. 2009). While these planets have masses approaching the Earth's, it remains unclear whether they are Earth-like with solid surfaces, or instead miniature Neptunes with massive envelopes of H and He (Valencia et al. 2007; Barnes et al. 2009). This issue will soon be addressed by the detection of transiting super-Earths around nearby, bright ($V < 9$) stars, for which Doppler follow-up can provide pricise mass measurements. The recent demonstrations of sub-millimagnitude ground-based transit photometry, together with the growing number of low-mass planets in short-period orbits, suggest that the first transiting super-Earth will be detected in the near future (Johnson et al. 2009; Gillon et al. 2008; Winn et al. 2009).

Searching for Earth-analogs around Sun-like stars is best pursued above the Earth's atmosphere. The COROT and *Kepler* space missions will provide continuous high-precision photometric monitoring of hundreds of thousands of stars within select patches of the sky to detect planets with a wide range of masses and orbital characteristics. Early results from COROT demonstrate the advantages afforded by observing from space, both in terms of attainable photometric precision and continuous temporal coverage, which increases detection sensitivity at longer orbital periods compared to ground-based surveys (Aigrain et al. 2008). The *Kepler* mission launched successfully in March of this year and will maintain a photometric precision of 20 $m$mag over the course of four years (Borucki et al. 2004). The precision and time baseline of *Kepler* will provide a galactic census of terrestrial planets around Sun-like stars out to separations of 1–2 AU. The transiting systems detected by *Kepler* and COROT will open up exciting new science directions for the next generation space observatories such as the James Webb Space Telescope (JWST), such as atmospheric transmission spectroscopy and measuring the phase variations of thermal and reflected light (Seager et al. 2008).

The "holy grail" is the imaging detection, and subsequent spectroscopic study, of a terrestrial planet in the habitable zone of a nearby star. Space-borne astronometry will provide a means of detecting and directly measuring the masses and orbital configurations of terrestrial planets. One such mission on the near horizon is the *Space Interferometry Mission* (SIM-Lite), which will provide an astrometric precision of better than 1 μas (Shao & Nemati 2008). Once Earthlike planets are identified, high-contrast imaging using techniques such as adaptive optics and coronography can be brought to bear to measure colors, and possibly even spectra, to search for biosignatures. Ground-based imaging surveys are making impressive strides, and planet searches are now beginning with the NICI campaign (Artigau et al. 2008; Liu et al. 2009 in press) and in the near future with the Giant Planet Imager (Macintosh et al. 2008), with the goal of detecting Jupiters in wide orbits. The technology developed for and proven by these surveys will inform future imaging efforts from space, such as the *Terrestrial Planet Finder* (Beichman et al. 2004).

In just 14 years, conceptions of planets around other stars have evolved from science fiction to a mature field of scientific inquiry. The next decade holds much promise as we progress toward the discoveries of solar systems like our own around other stars.

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